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(74) Agent: **KILBURN & STRODE**; 20 Red Lion Street, London WC1R 4PJ (GB).

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(71) Applicant (*for all designated States except US*): **IMPERIAL COLLEGE INNOVATIONS LTD** [GB/GB]; Electrical and Electronic Engineering Building, Level 12, Exhibition Road, London SW7 2AZ (GB).

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(72) Inventors; and

(75) Inventors/Applicants (*for US only*): **MORRISON, Jonathan, Finlay** [GB/GB]; Department of Aeronautics, Imperial College, London SW7 2AZ (GB). **DEARING, Stella, Silvana** [GB/GB]; Department of Aeronautics, Imperial College, London SW7 1AZ (GB). **ARTHUR, Graham, G.** [GB/GB]; Central Microstructure Facility, Rutherford Appleton Laboratories, Chilton, Didcot OX11 0QX (GB). **MCKEON, Beverley, Jane** [GB/GB]; Department of Aeronautics, Imperial College, London SW7 2AZ (GB). **CUI, Zheng** [GB/GB]; Central Microstructure Facility, Rutherford Appleton Laboratories, Chilton, Didcot OX11 0QX (GB).

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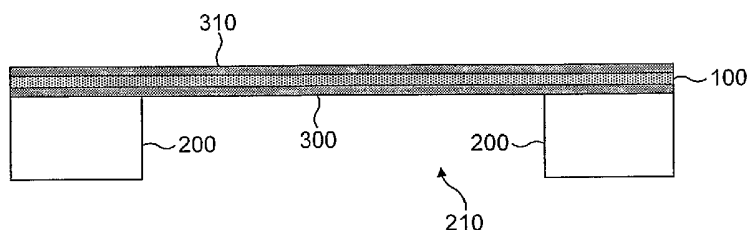
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(54) Title: FLUID FLOW CONTROL USING BOUNDARY LAYER CONTROL



(57) Abstract: A fluid flow control device (210) including an active actuator surface may be used to control boundary layer separation by controllably deforming the actuator surface to create a depression in an exterior face of the surface. Boundary layer control may thus be achieved by producing a turbulent state which is more resistant to separation than the original laminar flow by energising the boundary layer and preventing it from separating. The surface may comprise an electroactive polymer membrane (100) supported on a substrate (200) and a set of electrodes (300, 310) adjacent to a cavity in the substrate. The electrodes may be used to control the deformation of the electroactive polymer membrane to deflect into the cavity and thus create a depression. A fluid flow control system, vehicle, vessel, aircraft or stationary structure employing a fluid flow control device as described above is also envisaged. The fluid flow control device in a method of controlling a fluid flow over surface, including forming one or more depressions in the surface and varying the depths of the depression or depressions as a function of time.



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FLUID FLOW CONTROL USING BOUNDARY LAYER CONTROL

This invention relates to the control of the flow of fluids over surfaces, and in particular to a fluid flow control device, system and method.

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Due to its many practical applications, fluid flow past objects, such as, for example an aircraft wing or a car body, has been extensively studied in the past. For example, an aircraft wing is formed into a streamlined shape in order to increase its lift and, at the same time, reduce the aerodynamic drag exerted on the wing. In particular, in cases where boundary layer separation occurs, that is the fluid flow detaches itself from the surface, a wake region results downstream from the object. This has a number of undesirable consequences. For example, the pressure in the wake region tends to be lower than the surrounding pressure thus creating a net pressure force (pressure drag) which counteracts any movement of the bodies through the fluid. Moreover, once the boundary layer separates from the surface, it becomes highly unstable and will eventually roll into a discrete vortex, detached from the surface (vortex shedding). Vortex shedding creates a force at a frequency, which is a function of the Reynolds number and is related to the Strouhal number which is a dimensionless measure of the frequency of the vortex shedding.

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One of the main aims of devices for controlling boundary layer separation is to produce a turbulent state which is more resistant to separation than the original laminar flow. This can be achieved by increasing the vorticity of the boundary layer, thereby energising the boundary layer and preventing it from separating. There are many other potential applications of controlling vorticity, including the reduction of turbulent drag whereby a device introduces vortices that may counteract the effects of naturally occurring ones. There are also other flows in which the introduction of discrete vortices at a suitable time

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and location may be used to control the development of turbulent jets. Vorticity can be increased by static means, for example the dimples upon a golf ball, or by active flow control, discussed below.

5 Known flow control devices use periodic blowing for controlling boundary-layer separation for a wide range of Reynolds numbers including those typical of flight. This control concept is embodied in such devices as a synthetic jet operated by driving a diaphragm underneath an orifice with a periodic voltage so that it oscillates at its resonant frequency producing no net
10 mass flow out of the orifice, yet generating a net jet flow away from the orifice and into the boundary layer by a process similar to acoustic streaming. However there are many practical drawbacks to using synthetic jets, including the difficulty of controlling the actuation frequency, speed of response, and the most evident danger of ingesting dust.

15 On the other hand, the use of static dimples or depressions in the surface exposed to the flow in the control of laminar boundary layer separation is well known, especially in the application to golf balls, where the dimples induce a transition of the boundary layer by the generation of streamwise vortices. They
20 are much more effective than surface roughness since the hollow spherical shape produces cavity flow and thus the drag coefficient remains relatively constant at high Reynolds numbers.

 Aspects of the invention are set out in the independent claims, and
25 further, optional, features are set out in the dependent claims.

 By providing an active surface with a plurality of controllable depressions in the surface, active flow control may be achieved without the disadvantages of prior designs, referred to above. By using controllable

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depressions in a surface, embodiments of the invention have the advantage of acting within a continuous surface, thus incurring lower drag penalties while generating more localised vorticity than prior art vortex generators. The use of a continuous surface also avoids the problem of dust ingestion encountered in synthetic jets, which require a nozzle in the surface exposed to the fluid flow.

Embodiments of the invention are now described, by way of example only, with reference to the accompanying drawing in which:

Figure 1 shows a schematic representation of an actuator according to a first embodiment of the invention;

Figure 2 shows an electrode of the first embodiment;

Figure 3 is a magnified view of Figure 2;

Figure 4 shows a connection scheme for the electrode of Figure 2;

Figure 5 shows an actuator according to a second embodiment of the invention; and

Figure 6 shows an actuator according to a third embodiment of the invention.

A first embodiment of the invention is now described with reference to Figures 1 and 2. A thin dielectric elastomer film 100 (Med10 – 6607P or CF19-2186 Silicone by NuSil Inc, Carpinteria, CA, USA thickness of 20 microns, for example) is supported on a silicon wafer 200 (thickness 400 microns, for example). The wafer defines a plurality of cavities or apertures 210, whose size may range from a millimetre to a few millimetres. Adjacent to cavity 210, film 100, is sandwiched between a first and second electrode 300 and 310. First electrode 300 is situated between the silicon wafer 200/cavity 210 and the thin film 100, and the second electrode 310 is situated opposing the first electrode on the other side of the film.

Electrodes 300, 310 comprise concentric conducting rings 320 arranged around central disk 330. The conducting rings are connected to each other by conducting bridges 340 and the outermost ring is connected to a surrounded conductor 350 by conducting bridge 360. The conducting material may be a metal, for example a thin layer of gold. The electrodes are illustrated in Figures 2 and 3, the latter providing an enlarged view of Figure 2.

Figure 4 illustrates a connection scheme for the electrodes described with reference to Figures 2 and 3. The surrounding conductor 350 of the upper electrode 310 is connected to an energy source by a conducting track 370 on the upper surface of the film 100 and the lower electrode 300 is connected to its corresponding surrounding conductor (not shown in the Figure) by conducting track 380 supported between silicon wafer 200 and the lower surface on the film 100. As can be seen from Figure 1, most of the surface area of the lower electrode 300 is adjacent to cavity 210, the remaining surface area being supported on the silicon wafer 200.

When a potential difference is applied between electrodes 300, 310, the electric field induces a Maxwell stress in the film 100 due to the attraction between the charges on the electrodes. The film 100 is squeezed and expands in the plane of the film (the volume being conserved). As a result of the expansion in the plane of the film 100, the film will bend, upwards or downwards, in order to accommodate the increase of the lengths of the materials present between the walls of cavity 210. To obtain an actuator which, upon activation, produces a depression or dimple rather than a protrusion, it is necessary to ensure that the film will bend downwards into the cavity 210 rather than upwards from cavity 210. This can be achieved by, for example, providing the upper electrodes 310 with rings which are wider than the rings of the lower electrode 300, thus making the upper electrode less

flexible than the lower electrode and the lower side of thin film 100 more readily expandable than the upper side. The resulting structure will have an inherent bias to deform towards the cavity rather than away from it.

5 Briefly, to manufacture a device as described above, the silicon wafer 200 is covered on one side with an oxide layer for electric insulation. The patterned layers of the lower electrode, the dielectric elastomer and the upper electrode are formed sequentially by successive steps of applying a resist, patterning the resist, applying the electrodes (e.g. using evaporation of the metal) or the
10 dielectric elastomer (e.g. using spin-coating), and lifting off the resist to have the desired pattern. Of course, the elastomer has to be cured to some extent before applying the next layer for the upper electrode. A plurality of actuators can be formed in this way on the same wafer by appropriate patterning of the resist.

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Once the thin film 100 and electrode 300, 310 structure has been laid down, the cavity or cavities 210 are formed in the silicon wafer using standard etching techniques. It is necessary to ensure that the etching technique applied is compatible with the thin film dielectric elastomer in order to avoid damaging
20 of the thin film by the etching process. In addition the upper surface of the structure or active surface may be protected by applying a protective layer of suitably flexible polymer material, for example using the same material as for thin film 100.

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In use, the substrate 200 is secured to the object for which fluid flow is to be controlled (e.g. an aircraft wing) and the exterior face of the active surface is exposed to the fluid.

In a second embodiment, the patterned metal electrode of the first embodiment is replaced with a electrode formed from a conducting elastomer (CV-2646, NuSil Inc, diluted in naphtha, for example). The inherent elasticity of such an electrode avoids the need for an intricate structure of the electrode which is required to give sufficient elasticity to an electrode formed from a metal such as gold. A conducting elastomer electrode is able to stretch and follow the expansion of the central dielectric elastomer. Such an elastic electrode can be applied to the silicon wafer and, subsequently, film 100 using similar patterning/etching techniques as described in the context of the metal electrodes. However, the preparation of the electrodes is expected to be facilitated by fact the there is no need for intricate patterning associated with the metal electrodes.

Starting from a double side polished silicon wafer, an actuator with an elastomer electrode can be manufactured as follows:-

- Coat top side with silicon dioxide (electrical insulation)
- Coat with resist and pattern for dimple apertures
- Dry etch silicon dioxide and strip resist and clean
- Coat with resist and pattern for lower Cr/Au electrode connection
- Thermal evaporation of Cr/Au
- Lift-off to form lower Cr/Au electrode connections
- Coat with thick resist and pattern for lower conducting elastomer electrode
- Spin-coat lower conducting elastomer electrode
- Lift-off to form lower conducting elastomer electrode
- Spin-coat non-conducting dielectric elastomer layer
- Coat with thick resist and pattern for upper electrode
- Spin-coat upper conducting elastomer electrode

- Lift-off to form upper conducting elastomer electrode
- Coat resist and pattern for upper electrode Cr/Au connections
- Thermal evaporation of Cr/Au
- Lift-off to form upper Cr/Au electrode connections
- 5 • Coat resist on lower surface and pattern for dimple aperture
- Etch (DRIE) lower surface to form dimple apertures.

The resulting actuator is shown schematically in Figure 5. The entire material above cavity 210 is elastomeric (conducting elastomer 300, dielectric elastomer 100 and conducting elastomer 310). In addition, gold or chromium (or any other suitable metal) contacts have been provided for each electrode to the side of the cavity (351, 352 corresponding to the surrounding conductor 350 of the metal electrode.)

15 A third embodiment is illustrated with reference to Figure 6, and comprises a number of layers of dielectric elastomer, each sandwiched between two corresponding electrodes. Thus, a structure having n layers of dielectric elastomer will have $n+1$ layers of electrodes. For example, Figure 6 illustrates an embodiment having two dielectric elastomer layers 101 and 102 and three electrode layers 301, 302, 303 that is bottom, middle and upper electrode layers respectively. The third embodiment can be based on either the first or second 20 embodiments - metallic or elastomeric electrodes may be used, or indeed both.

The multilayer sandwich of the third embodiment is, in effect, two 25 actuators stuck together. The lower actuator can be operated, as before by applying a voltage between the bottom and middle electrodes and the top actuator can be operated by applying a voltage between the middle and top electrodes. With both actuators operating, the resulting expansion will be the same linear amount but have twice the force in the direction of stretch with

only 50% more electrodes (3 instead of 2). While an increased force might be obtained from a single actuator, as in the first and second embodiment, by increasing the applied voltage, this may exceed the breakdown voltage of the elastomer and lead to its failure. The stacked actuators alleviate this problem if
5 a higher force output is required.

In addition, if different voltages are applied to the top and bottom of the actuators then the resulting movement can be biased towards the cavity by applying a lower voltage to the lower actuator than to the upper actuator. Of
10 course, movement may be biased in the other direction to form a bump rather than a depression by applying a higher voltage to the lower actuator.

A fluid flow control device comprising a plurality of activators as described above can be manufactured by providing a plurality of actuators on a
15 single silicon wafer or by distributing single actuators or sets of actuators across the surface of the object subject to fluid flow control. For example such an object may be a car body, an airplane wing or any vehicle, vessel, aircraft or part thereof. A fluid flow control system comprising such a device and a corresponding controller can thus be used to optimise the fluid flow across the
20 object. The depth of the depression and its diameter will depend on the actual application. A starting point is a diameter of the order of the boundary layer thickness and a depth of the order of one tenth of the diameter.

In a first control mode, the electrodes of all or a subset of the actuators
25 are continuously energised, thus forming a dimpled surface with a plurality of static depressions. The first control mode can be used to switch between a state where a smooth, non-dimpled surface is preferable to a state where the presence of depression is preferable. For example, different parts of the surface subject to the fluid flow may be activated to provide dimples, depending on for

example the velocity of the fluid flow. As described in more detail below, the presence of boundary layer separation and the associated turbulence at a certain location on the surface can be detected by the control system. Corresponding actuators can then be actuated to counteract separation at that location. For
5 example, as the speed of a car varies, the separation region may shift and the controller may act to track the shifting separation region to provide a dimpled surface only where necessary.

In a second control mode, the controller does not continuously activate
10 the actuators, but rather produces an oscillation by providing a driving signal which varies over time. For example, the driving signal may vary as a periodical function of time having a fixed frequency.

In a feed-forward control mode, the actuators may be activated
15 according to a model of where boundary layer separation is expected to occur and of the predicted frequency of vortex shedding in the separation region. Actuators can be provided in likely separation regions given the geometry of the object. Variables such as the velocity of the object relative to the fluid can also be taken into account to actuate only those actuators which are likely to be
20 within a separation region, as determined by the model

In a feedback mode of control, pressure sensors incorporated into the surface of the object can be used to detect a separation region by measuring temporal fluctuations of the local pressure, or by measuring the gradient along
25 the direction of the flow. Turbulence resulting from an unstable separating boundary layer can be detected as local pressure fluctuations over time and an adverse pressure gradient (pressure increasing in the direction of the flow) is an indication that the boundary layer separation is occurring or is likely to occur in the region in question. Thus, a measurement of the pressure gradient can be

used for controlling fluid flow to avoid boundary layer separation as much as possible, and temporal fluctuations can be used to detect existing separation.

Based on the detection of a separation region as described above, an appropriate location for activating one or more actuators will be slightly upstream of the detected separation region. If the second control mode is used, the optimal actuation frequency will depend on the vortex shedding frequency at the location in question and it has been found that if the actuator is actuated at the Strouhal frequency corresponding to the separation reason in question, the choice of location of activation is less critical than otherwise.

In a feedback mode of control, as described above, one or more sensors have to be incorporated in the surface exposed to the fluid flow. Although any kind of pressure sensor can be envisaged for this purpose, an attractive solution is to use an actuator as described above both as an actuator and a sensor. This is possible because, in general, the capacitance between a pair of plate electrodes is proportional to the separation of the two electrodes. As any external pressure will result in the film 100 being stretched further than can be expected from the application of the voltage between the electrodes alone, measuring the thickness of the film 100 by measuring the capacitance of the actuator and comparing the result to the expected thickness can thus be used to provide a measurement of the external pressure applied to the actuator.

With appropriate instrumentation, the actuator structure described above can thus be used simultaneously as an actuator and a sensor. The capacitance of the actuator can be measured, for example, by injecting short current pulses, much shorter than the time constant of the actuator and measuring the voltage response characteristic of the capacitance. Even at quite large strains the electrostatic response dominates and the electric field output is proportional to

the square root of the strain. By comparison, conventional surface shear – stress gauges driven by thermal anemometry offer a voltage signal that is roughly proportional to the sixth root of surface shear stress.

5 The design requirements for a pressure sensing surface are somewhat different than for an actuator for forming depressions in the surface: for a sensing surface, a polymer with a low Youngs modulus and a high relative permittivity is required.

10 A first solution to this problem relies on the third embodiment comprising multiple layers of dielectric elastomeric material. In a combined sensor/activator design, one of the layers could be replaced with a dielectric elastomer suitable for the sensing application while the remaining layers remain unchanged. The sensing layer is then used to measure the external
15 pressure as described above while the other layers are activated for the formation of the surface depression (of course, if a material meeting both the design criteria for sensing and actuation is used, any one of the layers may be used for sensing). The second solution is to provide two different types of the actuator structure described above, one used for actuation and adapted
20 accordingly and one used only for sensing. Given the relatively small size and high density in which the actuators described above can be manufactured on a wafer this provides a viable alternative to designing a multi layer structure using different elastomeric materials.

25 While the above embodiments have been described with a reference to silicon wafer as a support, it will be apparent to the skilled person that any other suitable material can be used instead. Similarly, it will be apparent to the person skilled in the art to use electro-active polymers other than dielectric

elastomers, for example electrostrictive elastomers. Manufacturing techniques different from the silicon wafer technique described above are also envisaged.

An alternative manufacturing technique is to use ink jet printing to apply the electrode to the dielectric elastomer (or, more generally, electro active polymer). This represents an economic and fast alternative to the silicon wafer technique described above. The formation of an actuator (or sensor) can be achieved in the following manner:

- 10 • A membrane of dielectric elastomer material is imprinted on opposing sides thereof with a conducting polymer to form an electrode of a suitable shape, for example a disc shape, as described above. The electrodes are printed on opposed sides of the membrane so as to overlap substantially completely. Electrically conductive connections to the electrodes are also printed on the respective sides of the sheet with a conducting polymer.
- 15 • In order to be suitable for inkjet printing, the polymer needs to be more dilute and the polymer to solvent ratio needs to be decreased as compared to the spin-coating process described above (where a treacle-like consistence is appropriate).
- 20 • In order to provide a support structure or member defining the actuator in a similar fashion as cavity 210 in Figure 1, a rigid support or substrate may be provided, corresponding to the silicon wafer 200 of Figure 1, which has cut outs corresponding to the electrodes printed on the electrode sheet, corresponding to aperture 210 of Figure 1. The elastomer membrane is then secured to the support using a suitable adhesive such that the electrodes overlap with the cut outs. It is understood that any suitable material may be used for the support, for example a plastic material such as thermo- plastic or thermo-set material
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or a metal. In the latter case the metal or the electro-active sheet may have to be coated with an insulating material in order not to short-circuit the electrodes printed on the sheet. Of course, it is equally understood that the cut outs in the support may be replaced with blind holes opening towards the sheet.

- In an alternative embodiment, a support structure is laid down on the membrane either over-lapping or surrounding the electrode by ink jet printing, printing a rigid ring, rim or other suitable structure around or on the printed electrodes. The ring may be printed on one or both sides of the sheet. By forming a rigid boundary around the elastic material, the ring fulfils the same function as the silicon wafer 200/cavity 210 described above with reference to Figure 1. A suitable polymer for the rigid structure is Polyurethane Deerfield PT6100S (Deerfield Urethane, Inc. A Bayer Material Science Company P.O. Box 186 South Deerfield, MA 01373), which has a Young's modulus ten times larger than CF19-2186 Silicone by NuSil Inc.

- In a further alternative embodiment, the electroactive elastomer, electrodes and, where applicable, the support structure can be printed on an elastic support sheet, with the rigid support either superimposed or surrounding the dielectric elastomer and/or electrodes. A rigid structure in the same layer as the dielectric elastomer or electrode can be achieved either by printing a different polymer or by using an elastomer made from a two-part mix of hardener and resin. In the latter case, the relative local concentration of hardener and resin can be controlled by printing varying respective quantities, providing the droplet size is sufficiently small to ensure adequate mixing of the two components. In use the support membrane may be exposed to the fluid flow on a side opposed to the side carrying the electrodes and electroactive polymer, thereby

protecting them. Alternatively, the support membrane may be mounted in the opposite orientation.

5 The inkjet printing technique can further be advantageously applied to the present invention by integrating all or some of the sensing and control circuits on the elastomer sheet. For example, a Wheatstone bridge for pressure sensing can be implemented in a manner which is evident to the skilled person by printing suitable conductive and resistive elements directly on to the membrane or support sheet. One of the resistive elements may be a
10 suitable conducting polymer printed on the sheet such that it stretches with pressure, the Wheatstone bridge detecting the associated change in resistance to provide a pressure signal.

Furthermore, control, sensing and processing circuits, including transistors
15 can be printed directly on to the sheet. The printing of transistors comprises 5 main steps (see *Sirringhaus, H., Kawase, T., Friend, R.H., Shimoda, T., Inbasekaran, M., Wu, W. and Woo, P. 2000 "High-resolution inkjet printing of all polymer transistor circuits", Science 290, 2123* which is hereby incorporated herein by reference):

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- The electro active sheet may be surface energy patterned on at least one side to enable high resolution printing.
 - A conducting polymer is printed to create transistor source/drain electrodes.
 - Semi conducting polymer is printed to cover the electrodes.

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 - A dielectric layer is deposited, for example by spin coating.
 - A conducting polymer gate electrode is printed.
 - Capacitors, resistors and any other circuit elements which are required are printed and conducting tracks between the circuit elements are printed using a conducting polymer.

Further information on inkjet printing of circuit elements and polymers in general is disclosed in "*Printing Circuits*" *EPSRC Newslines Spring 2004*, <http://www.plasticlogic.com/index.php>, Calvert, P. 2001 "*Inkjet printing for materials and devices*". *Chem. Mater.* 13, 3299, all of which are hereby
5 incorporated herein the reference.

It will be apparent to the skilled person that the inkjet manufacturing technique can be used in combination with the disclosure of any of the
10 structures described above, where appropriate.

Although the embodiments described above have been described with reference to a dielectric elastomer, it will be understood that suitable electro-active polymers other than a dielectric electro-active elastomers may be used
15 instead.

In relation to the first embodiment, a patterned metal electrode has been described with a centre of symmetry. The use of such an electrode results in a depression with a symmetry corresponding to that of the electrode. As a
20 further development, an asymmetric electrode may be used, for example one with a higher area coverage to one side than to the other. Such an electrode would result in a higher expansion of the thin film 100 where the area coverage of the electrode is higher and will thus result in an asymmetric depression where the deepest point lies off the depression's centre. Such a device may be
25 favourable in certain applications, as it concentrates the vorticity produced by the depression at one side of the depression.

The embodiments discussed above describe an active surface for fluid flow control applications. It will be apparent to a skilled person that such an

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active surface can be employed in a number of contexts in addition to the ones mentioned specifically above. The embodiments described above are meant to illustrate, by way of example only, the invention, which is defined by the wording of the claims set out below.

CLAIMS

1. A fluid flow control device including an active actuator surface, an exterior face of which is arranged to be exposed to a fluid, the actuator surface being controllably deformable to create a depression in the exterior face.
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2. A fluid control device as claimed in claim 1 including a substrate in which the surface comprises an electro-active polymer membrane supported by the substrate on a first side; the surface membrane and the substrate co-operatively define an actuator; and wherein the depression is formed in a second side of the membrane when the actuator is active.
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3. A fluid flow control device as claimed in claims 2, the substrate defining a cavity; and the actuator including a set of two opposing electrodes, a first electrode on the first side of the membrane and a second electrode on the second side of the membrane, the electrodes being located adjacent to the cavity.
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4. A fluid flow control device as claimed in claim 3, the electrodes including a plurality of concentric metallic rings, adjacent rings defining a gap therebetween and being connected by metallic bridges.
5. A fluid flow control device as claimed in claim 4, some of the rings of the second electrode being wider than the rings of the first electrode.
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6. A fluid flow control device as claimed in claim 3, the electrodes including a conducting elastomer.
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7. A fluid flow control device as claimed in claim 1 in which the actuator surface includes a membrane of electro-active polymer, first and second

aligned elastomeric conducting electrodes, one printed on each side of the membrane; and a rigid member which is substantially more rigid than the membrane; the member substantially constraining an edge portion of the first and second electrodes and the membrane therebetween such as to define an actuator.

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8. A fluid flow control device as claimed in claim 1 in which the actuator surface includes a second elastomeric conducting electrode printed on a first face of an elastic support sheet; an electro-active polymer membrane printed on the second electrode; a first elastomeric conducting electrode printed on the membrane aligned with the second electrode; and a rigid member which is substantially more rigid than the membrane; the member substantially constraining an edge portion of the first and second electrodes and the membrane therebetween such as to define an actuator.

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9. A fluid flow control device as claimed in claim 8, a second, opposed face of the support sheet defining the exterior face.

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10. A fluid flow control device as claimed in claim 7, claim 8 or claim 9 in which the rigid member is printed on the surface and is preferably ring-shaped.

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11. A fluid flow control device as claimed in any one of claims 6 to 10, the second electrode being wider in a direction perpendicular to the surface than the first electrode.

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12. A fluid flow control device as claimed in any one of claims 6 to 11, the first electrode having a lower Young's modulus in the plane of the surface than the second electrode.

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13. A fluid flow control device as claimed in any one of claims 2 to 12, the membrane including n layers of electro-active polymer and a set of $n+1$ electrodes, a first electrode on the first side of the membrane, a second electrode on the second side of the membrane and a further electrode or
5 further electrodes therebetween such that each layer of electro-active polymer is sandwiched between a pair of electrodes.
14. A fluid flow control device as claimed in claim 13, including a sensor electro-active polymer layer having a higher permittivity than the remaining electro-
10 active polymer layers.
15. A fluid flow control device as claimed in any one of the preceding claims, comprising a plurality of actuators.
- 15 16. A fluid flow control device as claimed in any one of claims 2 to 15 including polymeric circuit elements, preferably including transistors printed on the substrate or surface.
17. A fluid flow control device as claimed in any one of claims 2 to 16, the
20 membrane including a dielectric elastomer.
18. A fluid flow control system comprising a device as claimed in any one of the preceding claims and a controller operatively connected to the electrodes of
25 the actuator or plurality of actuators to supply a voltage therebetween.
19. A fluid flow control system as claimed in claim 18 when dependent on claim
10, wherein the controller is arranged such that the voltage applied to an electro-active polymer layer adjacent to the first side of the membrane is larger
30 than the voltage applied to the electro-active polymer layer adjacent to the second side.

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20. A fluid flow control system as claimed in claim 18 or claim 19, wherein the controller is arranged such that the voltage varies as a function at times.
- 5 21. A fluid flow control system as claimed in claim 20 wherein the controller is arranged such that the voltage varies at a fixed frequency.
22. A fluid flow control system as claimed in claim 21, wherein the controller is arranged such that the frequency is determined by a Strouhal number of a flow to be controlled.
- 10 23. A fluid flow control system as claimed in any one of claims 18 to 22, including a readout circuit arranged to detect a voltage from an electrode representative of a pressure applied to the second side of the membrane at said electrode.
- 15 24. A fluid flow control system as claimed in claim 23 when dependent on claim 11, wherein the voltage is detected at the sensor layer.
- 20 25. A vehicle, vessel, aircraft, or stationary structure exposed to a fluid flow comprising a system as claimed in any one of claims 18 to 24, wherein the exterior face of the device is in contact with the surround of the vehicle, vessel, aircraft or stationery structure.
- 25 26. A vehicle, vessel, aircraft or stationary structure as claimed in claim 25, wherein the controller is arranged to detect a separation region of a boundary layer and to activate one or more actuators situated up-stream of the separation region.
- 30 27. A vehicle, vessel, or stationary structure as claimed in claims 25 or 26, wherein the controller is arranged to detect a vortex shedding frequency, and to activate one or more actuators at a frequency substantially equal to the vortex shedding frequency.

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28. A method of controlling a fluid flow over a surface, the method including forming one or more depression in the surface and varying the depths of the depression as a function of time.

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29. A method as claimed in claim 28, wherein the depth of the depression is varied as a periodic function of time.

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30. A method as claimed in claims 28 or 29, wherein the periodic function has a frequency determined by an estimate of the Strouhal number of the flow.

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31. A method of manufacturing a device as claimed in claims 1 or claim 7 including printing a conducting polymer onto both sides of an electro-active polymer sheet to form a pair of opposed, aligned electrodes; and securing a rigid member to the sheet or electrodes such that the member substantially rigidly constrains an edge portion of the pair of electrodes and the sheet therebetween.

20

32. A method of manufacturing a device as claimed in any one of claims 1 or claim 7 including printing a conducting polymer onto a flexible membrane to form an electrode; printing an electro-active polymer onto the electrode; printing a conducting polymer onto the electro-active polymer to form a pair of opposed, aligned electrodes; and securing a rigid member to the sheet or electrodes or electronic polymer such that the member substantially rigidly constrains an edge portion of the pair of electrodes and the electro-active polymer therebetween.

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33. A method as claimed in claim 30 or claim 31, including printing the rigid member on the sheet or electrodes or electro-active polymer, preferably in annular shape.

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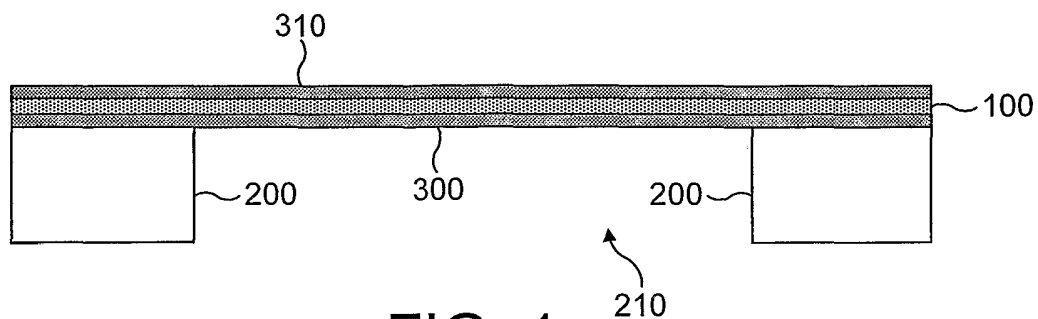


FIG. 1

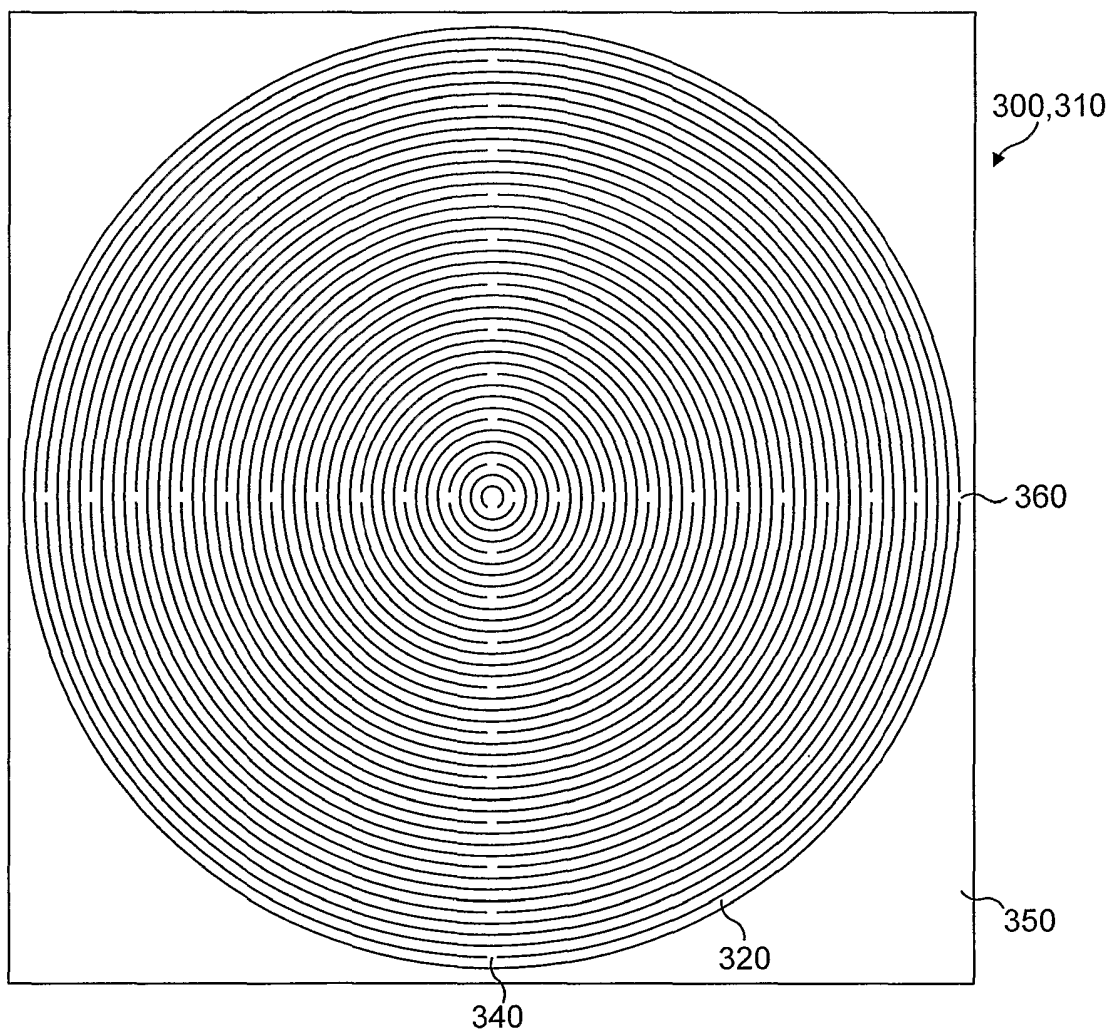


FIG. 2

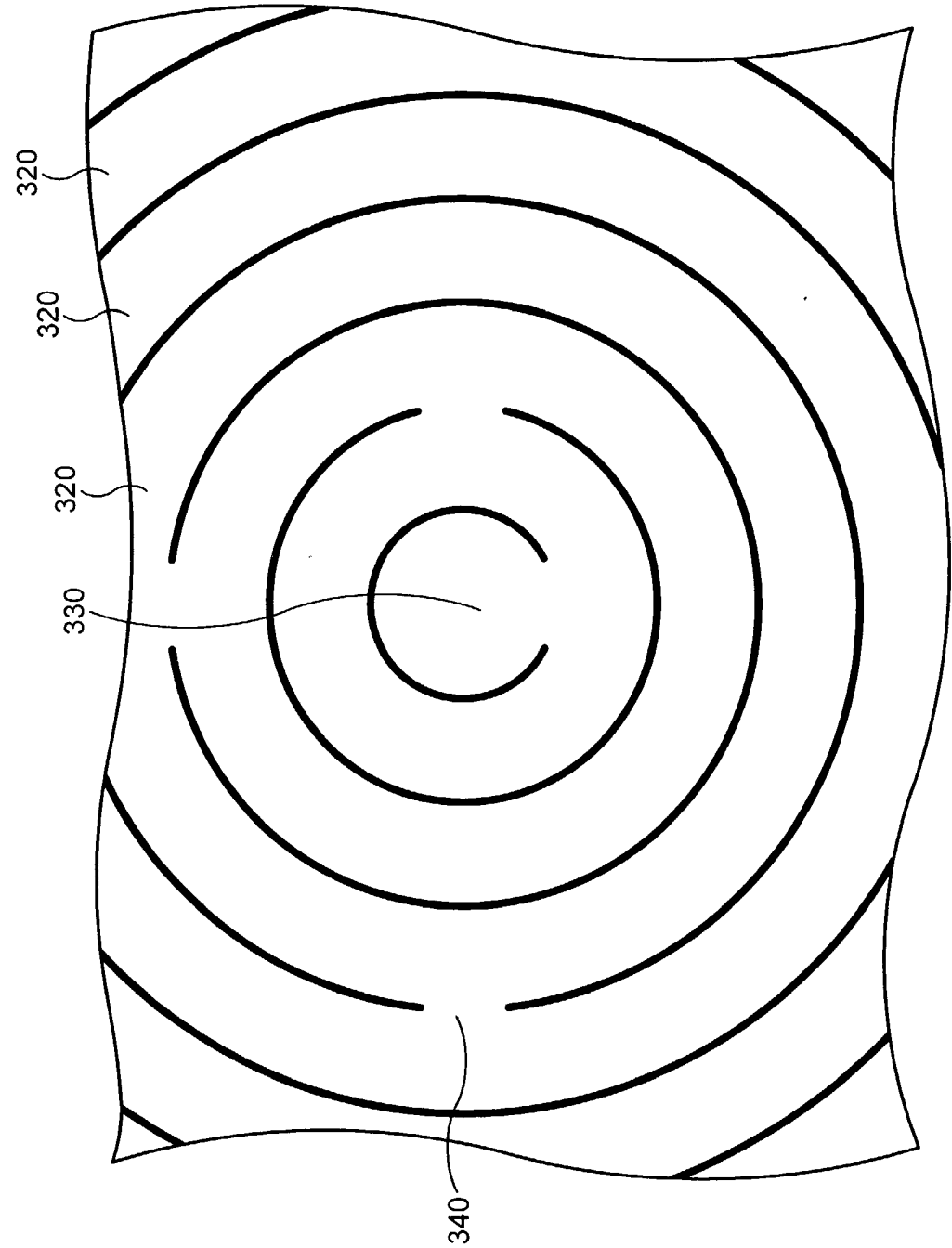
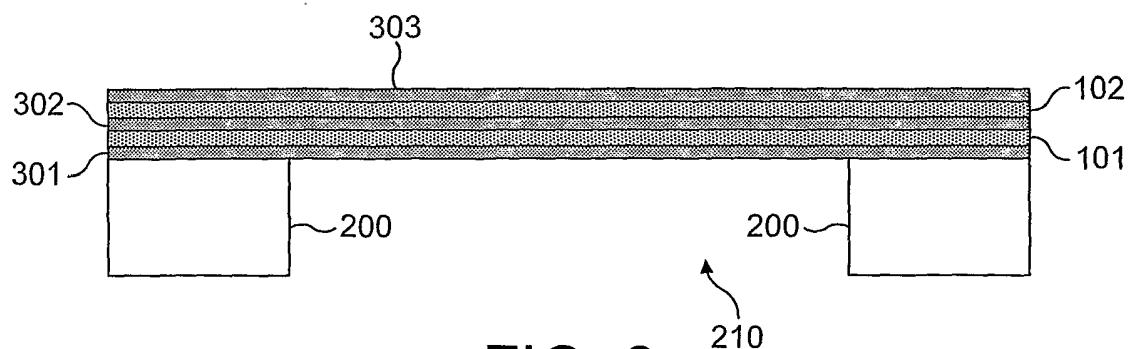
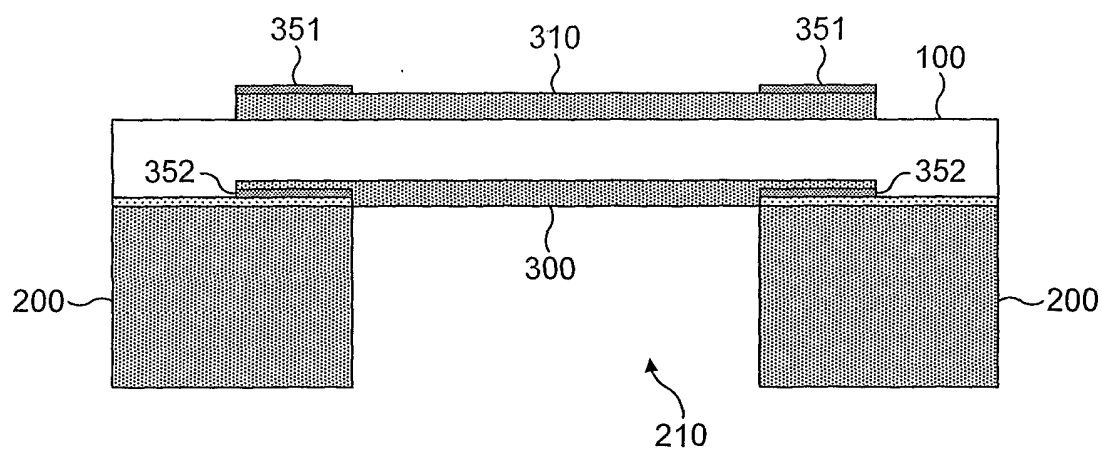
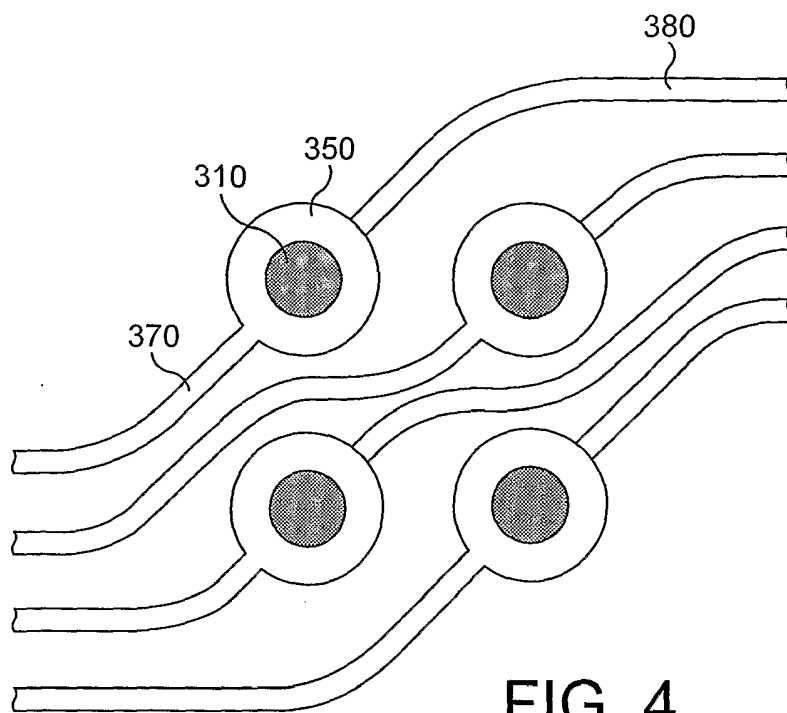


FIG. 3

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INTERNATIONAL SEARCH REPORT

Application No

PCT/GB2005/003894

A. CLASSIFICATION OF SUBJECT MATTER

F15D1/12 B64C23/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F15D B64C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|------------|--|---|
| X | <p>SINHA S K ET AL: "ON CONTROLLING FLOWS WITH MICRO-VIBRATORY WALL MOTION" AIAA PAPER, AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS, NEW YORK,, US, no. 2000-4413, 17 August 2000 (2000-08-17), pages 1-11, XP008054544 ISSN: 0146-3705 paragraphs '02.1!, '03.1!, '03.2!; figure 1</p> <p style="text-align: center;">----- -/--</p> | <p>1-3, 15, 17, 18, 20-23, 25, 27-30</p> |



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

° Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search

12 December 2005

Date of mailing of the international search report

19/12/2005

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

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Rechenmacher, M

INTERNATIONAL SEARCH REPORT

Application No

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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| X | SINHA S K: "FLOW SEPARATION CONTROL WITH MICROFLEXURAL WALL VIBRATIONS" JOURNAL OF AIRCRAFT, AMERICAN INSTITUTE OF AERONAUTICS & ASTRONAUTICS, NEW YORK, US, vol. 38, no. 3, May 2001 (2001-05), pages 496-503, XP008054593 ISSN: 0021-8669 page 497 pages 500-503; figures 1-3 | 1,15,17, 18, 20-22, 25-30 |
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